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Giant Outbursts of the Eta Carinae-P Cygni Type

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Abstract.

I discuss the role of short-duration eruptive mass loss in the evolution of very massive stars. Giant eruptions of Luminous Blue Variables (LBVs) like the 19th century event of η Carinae can remove large quantities of mass almost instantaneously, making them significant in stellar evolution. They can potentially remove more mass from the star than line-driven winds, especially if winds are clumped such that O star mass-loss rates need to be revised downward. When seen in other galaxies as “supernova impostors”, these eruptions typically last for less than a decade, and they can remove of order $10 M_{\odot}$ as indicated by massive nebulae around LBVs. Such extreme mass-loss rates cannot be driven by radiation pressure on spectral lines. Instead, these outbursts must either be continuum-driven super-Eddington winds or outright hydrodynamic explosions, both of which are insensitive to metallicity. As such, this eruptive mode of mass loss could play a pivotal role for massive metal-poor stars in the early universe.

1. Introduction

The main question I wish to address here is whether the majority of mass lost during the lifetime of the most massive stars occurs primarily via steady line-driven stellar winds, or instead through violent, short-duration eruptions. The two extremes are shown graphically in Figure 1. This is critical for understanding how \dot{M} scales with metallicity. In this contribution I draw attention to the role of LBV eruptions, advocating for their importance. The essential points of the argument, already made by Smith & Owocki (2006), are the following:

- Recent studies of hot star winds indicate that MS mass-loss rates are lower than previously thought due to the effects of clumping (Fullerton et al. 2006; Bouret et al. 2005; Puls et al. 2006; Crowther et al. 2002; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004). Revised \dot{M} values are inadequate to reduce the star’s mass enough to reach the WR phase.
- Observations of nebulae around LBVs and LBV candidates have revealed very high ejecta masses – of order $10 M_{\odot}$ (Fig. 2). Some objects show evidence for multiple shell ejections on timescales of 10^3 years. These eruptions could remove a large fraction of the total mass of the star.
- The extreme mass-loss rates of these LBV bursts imply that line opacity is too saturated to drive them, so they must instead be either continuum-driven super-Eddington winds (see Owocki et al. 2004) or outright hydrodynamic explosions. Unlike steady winds driven by lines, the driving in

these eruptions may be largely independent of metallicity, and might play a role in the mass loss of massive metal-poor stars.

For reasons that may be obvious, my talk at this meeting and the original paper (Smith & Owocki 2006) were deliberately provocative. Rather than repeat that discussion, I will briefly elaborate on a few of these issues, and will consider alternatives and further implications.

2. Balancing the Budget: LBV Eruptions

The most likely mechanism to rectify the hefty mass deficit left by clumped winds is giant eruptions of LBVs (e.g., Davidson 1987; Lamers 1987; Humphreys & Davidson 1994; Humphreys, Davidson, & Smith 1999; Smith & Owocki 2006), where \dot{M} and L_{Bol} increase substantially. While we do not yet fully understand what causes these giant LBV outbursts, we know empirically that they do indeed occur, and that they drive substantial mass off the star. Deduced masses of LBV and LBV-candidate nebulae are plotted in Figure 2. For stars with $\log(L/L_{\odot}) > 6$, nebular masses of $10 M_{\odot}$ are quite reasonable, *perhaps suggesting that this is a typical mass ejected in a giant LBV eruption.*

If these large nebular masses are typical for LBV outbursts, then only a few such eruptions occurring sequentially are needed to remove a large fraction of the star’s mass. This is shown schematically in Figure 1 for stars with initial masses of 120 and 60 M_{\odot} . Notice that at 60 M_{\odot} , the LBV eruptions are more numerous and each one is less massive than at 120 M_{\odot} ; this is mostly hypothetical, but is based on the presumption that a more luminous star will have more violent mass ejections because of its closer proximity to the Eddington limit. For example, we might expect that η Car currently has an Eddington parameter of $\Gamma=0.9$ or higher, whereas a less luminous LBV like P Cygni probably has $\Gamma=0.5$ or so. It is therefore also likely that the relative importance of eruptive mass loss diminishes with lower L . Measuring the mass ejected in each burst, plus their frequency and total number as functions of L and Z are probably the most important observations to unravel the role of LBVs in stellar evolution.

Our best example of this phenomenon is the 19th century “Great Eruption” of η Carinae. The event was observed visually, the mass of the resulting nebula has been measured (12–20 M_{\odot} or more; Smith et al. 2003), and proper motion measurements of the expanding nebula indicate that it was ejected in the 19th century event (e.g., Morse et al. 2001). The other example for which this is true is the 1600 AD eruption of P Cygni, although its shell nebula has a much lower mass (Smith & Hartigan 2006). Both η Car and P Cyg are surrounded by multiple, nested shells indicating previous outbursts (e.g., Walborn 1976; Meaburn 2001). While the shell of P Cyg is less massive than η Car’s nebula, it is still evident that P Cyg shed more mass in such bursts than via its stellar wind in the time between them (Smith & Hartigan 2006).

Although LBV eruptions are rare, a number of extragalactic η Car analogs or “supernova impostors” have been observed. Several massive circumstellar shells have also been inferred to exist around supernovae and gamma-ray bursters (see Smith & Owocki 2006 and references therein). These indicate that the eruption of η Car is not an isolated, freakish event, but instead may represent

a common rite of passage for the most massive stars. A massive ejection event may help initiate the LBV phase, by lowering the star's mass, raising its L/M ratio, and drawing it closer to instability associated with an opacity-modified Eddington limit (Appenzeller 1986; Davidson 1987; Lamers & Fitzpatrick 1988; Humphreys & Davidson 1994). In any case, meager mass-loss rates through stellar winds, followed by huge bursts of mass loss in violent eruptions at the end of core-H burning (Fig. 1) may significantly alter stellar evolution models.

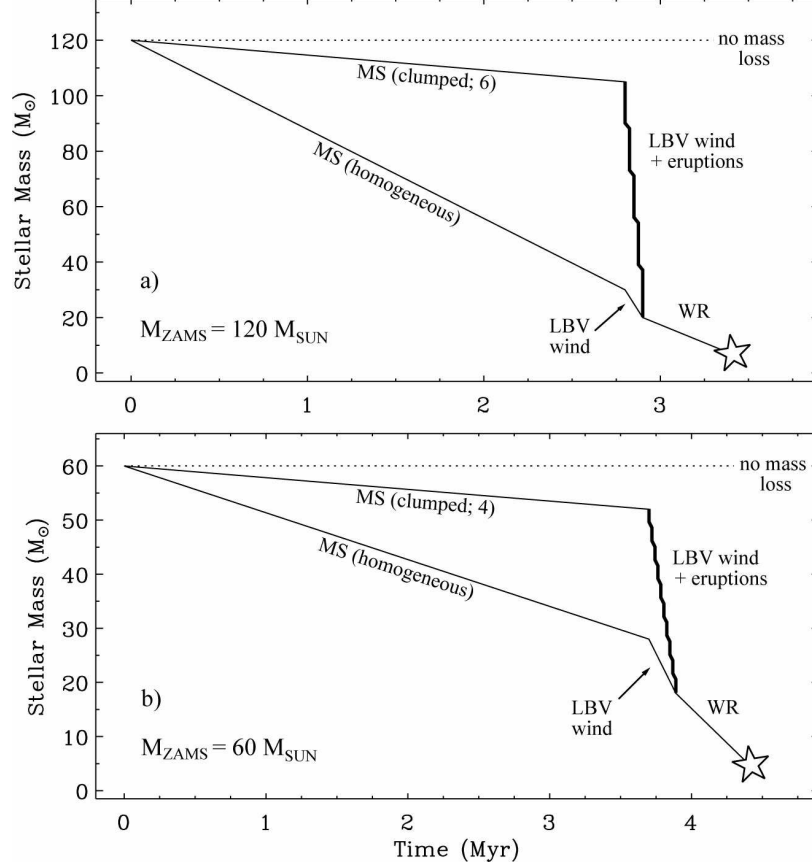


Figure 1. Schematic representation of a star's mass as a function of time. Two extreme scenarios are shown: One has higher conventional O-star mass-loss rates assuming homogeneous winds on the main-sequence (MS) with no clumping. This is followed by a brief LBV wind phase and a longer WR wind phase before finally exploding as a supernova; this is the type of scenario usually adopted in stellar evolution calculations. The second has much reduced \dot{M} on the main sequence (assuming clumping factors of 4–6), followed by an LBV phase that includes severe mass loss in brief eruptions plus a steady wind; this is the type of scenario discussed by Smith & Owocki (2006). Panel (a) shows the case for an initial stellar mass of $120 M_{\odot}$ (appropriate for an LBV like AG Carinae), and Panel (b) shows an initial mass of $60 M_{\odot}$ (appropriate for P Cygni, perhaps). The clumping factors of 4–6 shown here are still fairly modest compared to some estimates of >10 for O-star winds.

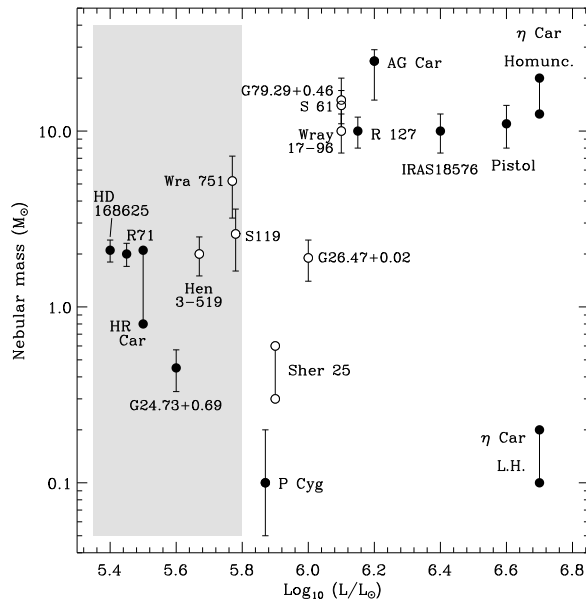


Figure 2. Masses of ejecta nebulae around LBVs (filled dots) and LBV candidates (unfilled) as a function of the central star’s bolometric luminosity. Luminosities are taken from Smith, Vink, & de Koter (2004), while sources for the masses are given in Smith & Owocki (2006).

3. Alternative Scenarios

The scenario where LBV eruptions dominate the mass loss of the most massive stars (Fig. 1), would represent a dramatic change in our understanding of mass loss in stellar evolution. The need for recognizing the role of LBV eruptions in mass loss is partly motivated by recent studies of the mass-loss rates of O stars, where wind clumping suggests drastic reductions in \dot{M} on the MS. To be fair, the amount of reduction in \dot{M} is not yet settled; some indications favor reduction of more than an order of magnitude, while other estimates indicate factors of only a few (see the talk by J. Puls). While this is debated, it is worth remembering that even if the \dot{M} reduction is only a factor of 3, *LBV eruptions may still dominate the total mass lost during the lifetime of a very massive star*. The plots in Figure 2 adopt fairly modest mass-loss rate reduction factors.

However, clumping in O-star winds is only part of the story. The other element is the observational reality that LBV eruptions like η Car’s massive 19th century outburst do indeed occur, and we have evidence that they occur more than once. A star’s mass budget needs to allow for that. However, if we require several 10’s of solar masses in LBV eruptions, plus enhanced mass loss during a WNL phase (see below), we run into a *serious* problem — homogeneous winds simply do not allow enough room for additional mass loss through WNL phases and LBV eruptions! Thus, the mass-loss rates implied by the assumption of homogeneous winds are not viable. I would then suggest that the existence of

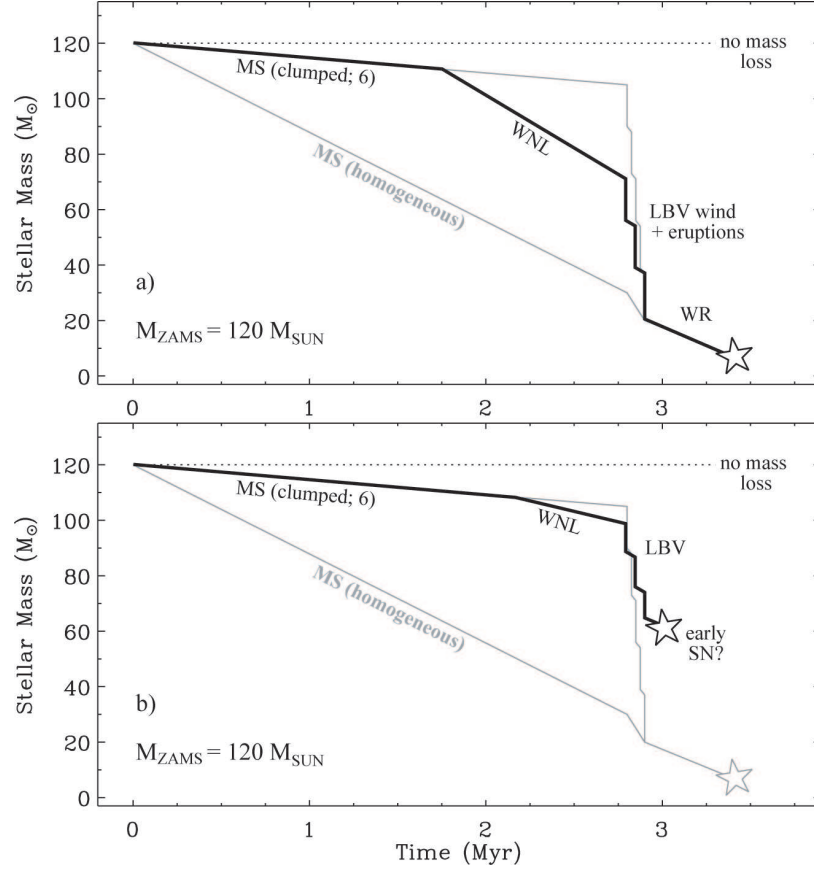


Figure 3. Same as Figure 1, but showing more complicated (and probably more realistic) hypothetical alternatives in between the two extremes of Figure 1a (only one case of $M_{\text{ZAMS}}=120 M_{\odot}$ is shown here). Panel (a) allows for substantial mass loss via a wind during an extended late-type WN phase that lasts for almost half the MS lifetime. The total mass lost by the WNL wind is almost as much as through LBV eruptions, but one could easily adjust these depending on the duration of the WNL phase. Panel (b) has a weaker WNL phase and allows for the possibility that the very most massive stars might explode before reaching the WR phase, thereby reducing the amount of mass that needs to be shed through LBV eruptions.

WNL and LBV mass loss is an independent argument that O star winds *must* be clumped, reducing \dot{M} by at least a factor of 2–3.

Of course, it is likely that neither extreme in Figure 1 is exactly right. The truth may lie somewhere in between, so let's consider two likely alternatives.

3.1. A Long WNL Phase?

One alternative is that a very massive star spends a good fraction of its H-burning MS lifetime as a late-type WN star (WNL; see Crowther et al. 1995). Even if their winds are clumped, WNL stars have higher mass-loss rates than

their O star counterparts. Thus, if massive stars can spend something like a third or half of their MS lifetime as a WNL star, they can take a substantial chunk out of the star’s total mass. This could temper the burden placed upon LBVs. This scenario is sketched in Figure 3a. To me, something like Figure 3a seems to be a “best bet”, but there are a few caveats to keep in mind.

First, Figure 3a with its rather long WNL phase should only apply to the most freakishly massive stars, with initial masses above roughly $90\text{--}100\text{ }M_{\odot}$. The justification for this comment is that spectral type O3 and even O2 stars still exist in clusters within star forming regions that are 2.5–3 Myr old (like Tr16 in the Carina Nebula). O3 stars probably have initial masses around $80\text{--}100\text{ }M_{\odot}$ or so, and MS lifetimes around 3 Myr. Therefore, these stars cannot spend a substantial fraction of their H-burning lifetime as a WNL star, because they evidently live for about 3 Myr without yet reaching the WNL phase (ask P. Conti for an alternative hypothesis). Only for the most massive stars might a relatively long WNL phase be possible. This makes me wonder if we have yet another a dichotomy in stellar evolution, with different evolutionary sequences above and below $100\text{--}120\text{ }M_{\odot}$ – much like the dichotomy above and below $45\text{--}50\text{ }M_{\odot}$. One could certainly make the case that the most luminous evolved stars that are sometimes called LBVs or LBV candidates – stars like η Car, the Pistol star, HD5980, and possibly LBV 1806-20 – have followed a different path than the “normal” LBVs like AG Car and R127. Below this threshold, hot supergiants like Ofpe/WN9 and B[e] stars might fill similar roles.

Second, while I admit that WNL stars make a substantial contribution to \dot{M} , their influence must be limited. They cannot provide the majority of mass lost by these stars, so the LBV eruption mass loss must still dominate. The reasoning behind this comment has to do with the available mass budget of η Carinae; namely, that η Car is probably a post-WNL star, *but it still has retained most of its original mass*.

Let’s remember that η Car is the most luminous and most evolved member of a rich region containing over 65 O-type stars, as well as 3 WNL stars (see Smith 2006). The current LBV phase of η Car is not only a post-MS phase, but probably also a post-WNL phase, since its ejecta are more nitrogen rich than the WNL stars in Carina. It is also reasonable to assume that η Car has advanced further in its evolution sooner than the WNL stars of the same age in this region simply because it is more luminous and started with a higher initial mass. Now, η Car is seen today surviving as a very massive star of around $100\text{ }M_{\odot}$, and we measure a total of something like $20\text{--}35\text{ }M_{\odot}$ in its circumstellar material ejected in only the last few thousand years (the Homunculus, plus more extended outer material; see Smith et al. 2003, 2005). That means η Car began its LBV phase – and ended its MS and WNL phases – with $\sim 120\text{ }M_{\odot}$ still bound to the star! If there really is an upper limit of about $150\text{ }M_{\odot}$ to the mass of stars (Figer 2005; Kroupa 2005), then *this rules out the possibility that winds during the MS or WNL phases could dominate the mass-lost by the star in its lifetime*.

This argument is made graphically in Figure 4, with options of “long” and “short” WNL phases. Keeping three facts in mind — **1.** that we see more than $20\text{ }M_{\odot}$ of nebular material from recent LBV eruptions around η Car, **2.** that η Car has a present day mass around $100\text{ }M_{\odot}$ if it is not violating the classical Eddington limit (I am being generous with the companion star’s mass in Figure

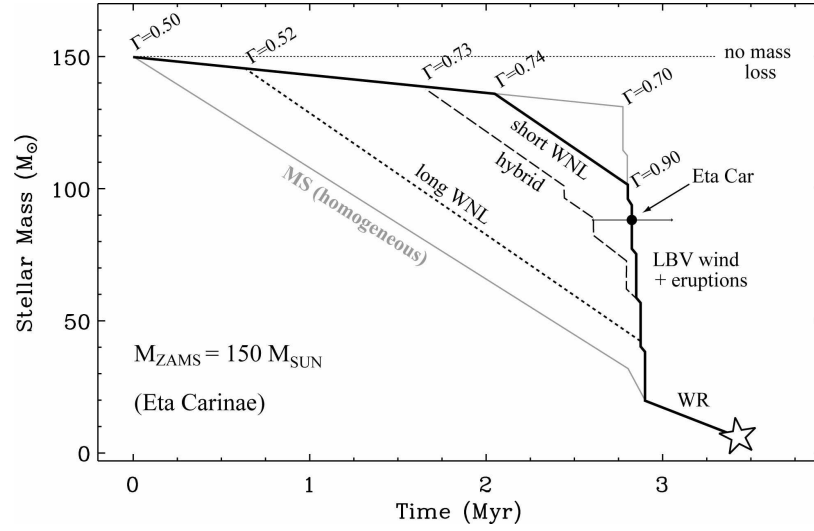


Figure 4. An artist’s conception of the mass-loss history for a star with an initial mass at the upper limit of $150 M_{\odot}$, perhaps appropriate for η Carinae. Here I show relatively short (small contribution) and a relatively long (dominant contribution) WNL phases, a “hybrid” WNL/LBV scenario, and the simpler extremes in gray. Representative Eddington factors along the way are indicated. The dot shows the likely currently-observed locus of η Carinae (note that I am being quite generous here with the correction for η Car’s companion star). Considering that η Car has already suffered 2–3 major LBV eruptions, which scenarios are consistent with its present mass?

4), and **3.** that there is a likely upper mass limit for stars of around $150 M_{\odot}$ — where could you place η Carinae on each track in Figure 4? What does that signify for the relative importance of the WNL phase?

Another not-too-ridiculous possibility may be the following: *What if the WNL and LBV phases overlap, so that WNL stars are quiescent LBVs for part of their existence?* This scenario is shown by the “hybrid” track in Figure 4. We already know that some LBVs (like AG Car) are classified as Ofpe/WN9 stars in quiescence and make the transition between the two states (Stahl 1986). Perhaps the more luminous WNL stars are also dormant LBVs for a spell. In any case, WNL stars do exist and their line-driven winds must play some role in stellar evolution; the relative contribution of WNL vs. LBV eruptions is a matter of degree, depending on the lifetime of the WNL phase.

Perhaps the most interesting consequence of the WNL mass loss is that **the WNL phase may facilitate the onset of the LBV instability.** By quickly reducing the star’s mass and thereby raising the star’s L/M ratio, the WNL wind may bring the star to the critical point where it is dangerously close enough to the Eddington limit (say $\Gamma \simeq 0.9$) such that the LBV instability kicks in and takes over the star’s mass loss. Representative Eddington factors are indicated along the various tracks in Figure 4, and make the point vividly. This raises interesting questions about what happens at very low metallicity, since the line-driven WNL wind should be weaker.

3.2. An Early Death at the End of the LBV Phase?

The main motivation for such huge amounts of mass loss in continuum-driven LBV eruptions is the assumption that even the most massive stars eventually need to reach the WR phase, requiring that their mass be whittled down to about $20 M_{\odot}$ before then (see Smith & Owocki 2006). If we can relax this constraint so that the most massive stars above $100 M_{\odot}$ perhaps *do not* make it to the WR phase, then we can alleviate the burden of removing so much mass through LBV explosions. In other words, *the most massive stars might undergo core collapse at the end of the LBV phase, instead of entering the WR phase* (Figure 3b). If this scenario were true, of course, it would mean that η Carinae and stars like it in other galaxies may explode as hypernovae at any moment.

We should be mindful that this alternative would require an *even more* radical paradigm shift in our understanding of stellar evolution than Figure 1a. Namely, Figure 3b would require that not only are LBVs in core He burning, but that LBVs reach more advanced stages. Yet, there are some reasons why an early explosion like in Figure 3b might be attractive:

- As noted earlier in §2, observations of SNe (especially type II_n) and GRBs reveal that some have dense, massive circumstellar shells. Where could these shells have come from if the WR phase has a sustained fast wind for a few 10^5 years? The answer may be that these shells did in fact originate in LBV outbursts that occurred within about 1000 years of the final death of the star. That would be astonishing and very important if true.
- In his talk at this meeting, Jorick Vink drew a similar conclusion about supernovae occurring at the end of the LBV phase, based on the radio evolution of objects like SN2001ig (e.g., Ryder et al. 2004).
- A. Gal-Yam et al. (2007; in prep.) have identified a likely LBV as the progenitor for the Type II_n SN2005gl, and there may be others.

4. Eruptive Mass Loss at Low Metallicity

Unlike line-driven winds, the driving mechanism for giant LBV outbursts is probably insensitive to metallicity (see Smith & Owocki 2006). There is good empirical evidence for this: Above $\sim 10^{5.8} L_{\odot}$, no RSGs are seen because their redward evolution is halted by heavy mass loss in the LBV phase (see many contributions in the pre-fire Lunteren meeting). This upper limit to RSGs seems to hold even in low Z environments like the SMC (Humphreys & Davidson 1979), implying that the LBV instability is indeed metallicity-independent.

The first stars, which were metal free, are thought to have been predominantly massive (e.g., Bromm & Larson 2004). With no metals, these stars should not have been able to launch line-driven winds, and thus, they are expected to have suffered no mass loss during their lifetimes. The lack of mass loss profoundly affects the star's evolution, the type of supernova it eventually produces (Heger et al. 2003), and its yield of chemical elements.

This view rests upon the assumption that mass loss in massive stars at the present time is dominated by line-driven winds, but this assumption may be

problematic because of the role of LBV outbursts and their metallicity independence. Furthermore, LBV mass loss in the first stars might enable a WR phase to occur, wherein the star could shed further mass through a line-driven wind because of self-enrichment (Vink & de Koter 2005; Eldridge & Vink 2006). If mass loss of massive stars at the present epoch is dominated by a mechanism that is insensitive to metallicity, then we must question the prevalent notion that the first stars suffered no mass loss before their final SN event. If these outbursts can occur at low metallicity, it would profoundly alter our understanding of the evolution of the first stars and their role in early galaxies.

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